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Biospheric primary production during an ENSO transition.

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cause the area of the Antarctic “ozone hole” to spread beyond those measured in the 1990s. Thus, the effect of denitrification on ozone recovery in both hemispheres cannot be ignored and must be included quantitatively in assessment models for better predictions of future springtime polar ozone trends.

References and Notes
14. Selective nucleation of just a few STS particles into more stable crystalline forms of nitric acid sets the stage for the differential growth process (10, 11), which results in the occurrence of a very small population of relatively large nitric acid hydrate cloud particles. It is the sedimentation of these large nitric acid hydrate particles that leads to denitrification.
21. The results of laboratory freezing rates are parameterized into simple functions of the form (20)

$$J_{\text{NAD}} = 1.138 \times 10^{-6} \text{ cm}^3 \text{ mol}^{-1} \text{ s}^{-1} \exp \left( \frac{-\Delta C_{\text{NAD}}^0}{RT} \right),$$

where

$$\Delta C_{\text{NAD}}^0 = (28.8 \pm 0.2) - (0.37 \pm 0.01)S_{\text{act}}^0$$

$$J_{\text{NAT}} = 9.269 \times 10^{-6} \text{ cm}^3 \text{ mol}^{-1} \text{ s}^{-1} \exp \left( \frac{-\Delta C_{\text{NAT}}^0}{RT} \right),$$

where

$$\Delta C_{\text{NAT}}^0 = (30.9 \pm 0.3) - (0.14 \pm 0.0004)S_{\text{act}}^0$$

where $j$ is the freezing rate of a single particle in cm$^3$ mol$^{-1}$ s$^{-1}$, $T$ is the temperature in K, $r$ is the particle radius in cm, $C_{\text{act}}^0$ is the activation energy for freezing of hydrate crystals into solution in units of kcal mol$^{-1}$ (20), $S$ is hydrate saturation in solution, and $R$ is the universal ideal gas constant in units of kcal mol$^{-1}$ K$^{-1}$. To account for the effect of particle size on freezing, we have slightly modified (35) the pre-exponential factor from that given in Salcedo et al. (20).
22. The 1D model uses vertical temperature profiles that are constructed using the archived NASA Goddard National Center for Environmental Prediction (NCEP) reanalysis temperature profiles, a single position is first selected on the 450 K surface (~50 mbar) inside a cloudy region (~T < 192 K). Next, air parcel trajectories (36) are run forward and backward for 2 weeks from the chosen location to obtain a 4-week-long temperature and position history of an air parcel. Positions along the 4-week-long trajectory at the 450 K level are used to read off vertical temperature profiles at each location and time along the parcel’s path using the NCEP data.
24. Cloud model sensitivity studies (22) indicate that hourly NAT and/or NAD particle hydration production rate $< 10^4 \text{ cm}^{-3} \text{ s}^{-1}$ (Fig. 3) can result in 10% denitrification at most in typical air parcels before particle evaporation occurs. Thus, NAT particle production within the nucleation window is the dominant process that controls the overall atmospheric number density of the nitric acid hydrated particles. Direct NAT particle production rate from STS is $< 10^3 \text{ cm}^{-3} \text{ s}^{-1}$ in the atmosphere (Fig. 1), making this process unimportant to denitrification. The temperature margins of the nucleation window vary as a function of total pressure, H$_2$O mixing ratio, and HNO$_3$ mixing ratio.
25. To compute cloud microphysical properties, 20 initial points were homogeneously distributed within the 192 K temperature contour at 50 mbar for the 3 days marked as dashed lines in Fig. 2. These days represent cloud conditions during the overall study period (marked as bowed arrows in Fig. 2). We ran trajectories forward and backward from each initial point to obtain 20 4-week-long air parcel temperature histories for each winter; their corresponding vertical temperature profiles are constructed as described above (22).
27. For standard model runs, mean $\Delta C$ values were used in the $j$ expressions for both NAT and NAD (21). Sensitivity studies were also performed by using upper and lower limits for $\Delta C$ in the $j$ expressions for both hydrates.
28. To account for NAT to NAD conversion in the model, the assumptions were used for $j$ values as follows: $j_{\text{NAT}} = \text{standard} \times [\text{standard} + \text{Satur} + \text{Satur}] = 0$ (27). Most laboratory observations indicate that the metastable NAT phase is the nucleus that initially

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Biospheric Primary Production During an ENSO Transition
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The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) provides global monthly measurements of both oceanic phytoplankton chlorophyll biomass and light harvesting by land plants. These measurements allowed the comparison of simultaneous ocean and land net primary production (NPP) responses to a major El Niño to La Niña transition. Between September 1997 and August 2000, biospheric NPP varied by 6 petagrams of carbon per year (from 111 to 117 petagrams of carbon per year). Increases in ocean NPP were pronounced in tropical regions where El Niño–Southern Oscillation (ENSO) impacts on upwelling and nutrient availability were greatest. Globally, land NPP did not exhibit a clear ENSO response, although regional changes were substantial.

Temporal changes in the physical environment are manifested in the light-harvesting capacity of plant communities throughout the tropics and can be monitored remotely by changes in surface chlorophyll concentration ($C_{\text{sat}}$) in the oceans and the Normalized Difference Vegetation Index (NDVI) on land. A continuous, 20-year global record of satellite NDVI has permitted characterization of interannual, climate-driven changes in terrestrial photosynthesis ($J$). Coincident changes in ocean productivity have not been assessed because an analogous long-term global $C_{\text{sat}}$ record does not exist. The first $C_{\text{sat}}$ measure-
ments were made with the Coastal Zone Color Scanner (CZCS: 1978–86), but this proof-of-concept sensor collected data on a highly irregular basis that yielded incomplete global coverage even after integration over the entire 8-year mission. Eleven years later, SeaWiFS was launched, marking the beginning of the first multiyear satellite measurements of phytoplankton biomass since CZCS. SeaWiFS now provides greater global coverage of C sat each month than was achieved throughout the lifetime of CZCS. In addition, SeaWiFS is the first satellite instrument with the spectral coverage and dynamic range necessary to derive both C sat and NDVI. Here we report spatial and temporal changes in the photosynthetic biosphere for an El Niño to La Niña transition period, as recorded during the first 3 years of the SeaWiFS mission.

We analyzed global, 4-km resolution, monthly SeaWiFS C sat and NDVI data collected between September 1997 and August 2000. Stability of the sensor was characterized from monthly lunar-based calibrations and derived products verified by comparison with field measurements (6–8). Biospheric net primary production (NPP) was estimated following the approach of Field et al. (9), which integrates the Vertically Generalized Production Model (VGPM) for the oceans (10) with the Carnegie-Ames-Stanford Approach (CASA) for land (11, 12). Variations in NPP for the CASA-VGPM model arise from changes in three factors: (i) incident photosynthetically active radiation (PAR), (ii) the fraction of radiation absorbed by plants (related to C sat and NDVI), and (iii) light use efficiency (e). Coincident changes in these factors collectively control NPP. Unlike previous calculations that used C sat, NDVI, and climate data from different periods (9), all data used in the current NPP estimates were collected during the SeaWiFS period (13). The CASA-VGPM model was operated on a monthly time step.

SeaWiFS measurements began near the peak of the 1997–98 El Niño event (by some measures, one of the strongest on record) and low PAR during winter months and then increases markedly in the summer when surface waters rich in nutrients become stratified and PAR is high. Consequently, NPP was strongly seasonal in this region, varying from 0 to 49 g C m⁻² month⁻¹ (Fig. 3). In contrast, seasonality in NPP was greatly dampened poleward of 40°S, with summer values decreasing from 27 to 7 g C m⁻² month⁻¹ between 40° and 70°S (Fig. 3). This absence of a high-latitude, Southern Hemisphere bloom results from weak seasonality in factors limiting phytoplankton growth, particularly iron and vertical mixing (16–19). We calculated that a 9 Pg C year⁻¹ increase in NPP would result if seasonal changes in phytoplankton biomass beyond 40° and 75°S paralleled those in the Northern Hemisphere (20).

On land, temporal changes in global mean NDVI were dominated by strong seasonal fluctuations, with minima of 0.44 ± 0.01 (dimensionless) between December and February and maxima of 0.55 ± 0.01 between June and September (Fig. 1B). Land NPP peaked between 15°S and 10°N, reaching 87 g C m⁻² month⁻¹, and varied seasonally at >35°N from 0 to 75 g C m⁻² month⁻¹ (Fig. 2, A and B). Despite the strong El Niño and La Niña, monthly anomalies indicated little systematic impact on global mean NDVI for the 3-year SeaWiFS record (Fig. 1B) (15). Land NPP was nearly constant for both climate regimes, ranging from 57 to 58 Pg of C year⁻¹ between September 1997 and August 2000. Substantial ENSO-related regional changes, however, are hidden in these global integrals.

Biospheric distributions of NPP register
spatiotemporal variations in light, soil moisture, nutrient availability, and temperature. Interannual variability in NPP is thus linked to regional changes in physical forcings that regulate these resources and environmental conditions. Particularly striking examples of this relation during the 1997–98 El Niño to La Niña transition included an increase in equatorial Pacific NPP resulting from enhanced upwelling (21) and reduced terrestrial NPP in eastern Africa related to decreased precipitation (Fig. 2C).

Additional features of the transition included (i) a change in Indian Ocean circulation that increased NPP in the northeast while decreasing productivity west of Indonesia (22), (ii) precipitation-related changes in NPP over Amazonia and Argentina, and (iii) nutrient-driven increases in ocean NPP east of Argentina and in the Mauritanian upwelling plume off western Africa (Fig. 2C). Persistent La Niña conditions between the Boreal summers of 1998 and 1999 led to La Niña to La Niña conditions resulted in substantial regional changes in NPP, as illustrated by interannual differences in Austral summer NPP (i.e., average NPP for December 1997 to February 1998 minus average NPP for December 1997 to February 1998). (D) Changes in NPP between two La Niña Boreal summers (1999 minus 1998). (C and D) Red, increase in NPP; blue, decrease in NPP; white, no substantial interannual change in NPP.

The CASA-VGPM model gave biospheric NPP estimates of 111 to 117 Pg C year$^{-1}$ for the September 1997 to August 2000 period (24). Using the same model and remote sensing data collected between 1978 and 1990, Field et al. (9) estimated biospheric NPP at 105 Pg C year$^{-1}$. Their estimate for the land component (56 Pg C year$^{-1}$) was about the same as that reported here. However, their estimate of ocean NPP (49 Pg C year$^{-1}$) was considerably lower than our results, largely because of higher $C_{sat}$ values from SeaWiFS (1997–2000) than from CZCS (1978–86) (9, 25).

Since September 1997, SeaWiFS has provided the first multiyear measurements of ocean plant biomass in over a decade, as well as the first single-sensor global observations of the photosynthetic biosphere. SeaWiFS NDVI and $C_{sat}$ data provide a basis for quantifying temporal changes in NPP, which is a critical component of global carbon and nutrient cycles. Land and ocean productivity responds to changes in the physical environ-
ment across the temporal continuum of climate variability, with seasonal cycles dominating over interannual changes (Fig. 1). Our initial analysis of the first 3 years of SeaWiFS data suggests that this sensor will have the capacity to detect longer time scale, lower amplitude responses of the photosynthetic biosphere to climate change. Achieving this goal will require a long-term commitment to intercalibrating optical observations and improved ε models (27) and remote sensing algorithms (27). As these developments are realized, the SeaWiFS record will provide a basis against which future estimates of Earth system elemental cycling can be compared.

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References and Notes
6. The SeaWiFS sensor is mounted on the OrbView-2 spacecraft (28) and follows a sun-synchronous orbit with a noontime equatorial crossing. The sensor provides complete 4-km global coverage every 2 days. The mission has operationally produced oceanic, atmospheric, and terrestrial data products since September 1997. The complete SeaWiFS data set has been reprocessed three times to incorporate refinements in sensor calibration, atmospheric correction, and bio-optical algorithms. The present study uses data from the most recent, May 2000 reprocessing (29). Monthly calibration images indicate a progressive decrease in sensitivity of <1% for the six visible wave bands and up to 10% for the near-infrared wave bands. By applying calibration corrections based on the lunar time series, temporal changes in radiometric sensitivity are corrected to within <1% (29, 30).
7. SeaWiFS wave bands relevant for deriving Csat values are 433 nm, 555 nm, and 667 nm. The third reprocessing of SeaWiFS data used the OC4 chlorophyll algorithm (29). Comparison of OC4 modelled and measured sea surface chlorophyll concentrations (29) is noteworthy, that between 0.07 and 5.0 mg Chl m⁻² (i.e., 93% of the global ocean), OC4-based Csat values are not substantially different than values derived from a single wave band ratio algorithm. Thus, the global-scale spatial and temporal patterns in Csat and ocean NPP described here are not strongly dependent on the choice of Csat algorithm.
8. For SeaWiFS NDVI data, cloud artifacts were reduced by applying a maximum 5 by 5 pixel spatial filter over evergreen broadleaf forest regions and a median 5 by 5 pixel spatial filter and a Fourier Filter over all other land surfaces (21, 32). Mising data for needle evergreen regions during winter at >45°N were estimated from October values. No statistically significant trends [95% confidence level] were introduced by these corrections. SeaWiFS NDVI data were calibrated with

1997–98 Advanced Very High-Resolution Radiometer (AVHRR) Fourier-adjusted, solar angle-corrected, interpolated, and reconstructed (FASIR) data (32) on a per biome basis to achieve compatibility with field NDVI and NPP data sets (27). SeaWiFS data were calibrated to within 0.0037 for interannual variations (Fig. 1). Our analysis of satellite orbit drift between September 1997 and August 2000 NDVI has, unlike some other vegetation indices, a consistent positive near-linear relation with the fraction of incident PAR absorbed by the vegetation canopy (FPAR) (23, 34).
13. For the oceans, ε modeled as a function of sea surface temperature (T). For land, the fraction of PAR absorbed by vegetation was calculated from NDVI (32) and ε was related to local variations in soil moisture and temperature. For the oceans, sea surface temperature fields coincided with AVHRR measurements. Monthly, 9-km resolution PAR fields were obtained from five SeaWiFS visible wave bands with an algorithm adapted from Frouin and Chertock (25). For land, PAR was taken as the sum of direct and diffuse visible radiation from monthly maps provided by the National Centers for Environmental Prediction (NCEP) [36]. Local soil moisture and temperature fields were obtained from the NCEP monthly precipitation and 2-m air temperature maps.
15. Detecting temporal changes in NPP is critically dependent on the thorough characterization of shift in instrument sensitivity. Complete descriptions of SeaWiFS calibration and analysis methodologies have been published (27). Positive near-linear relation with the fraction of incident PAR absorbed by the vegetation canopy (FPAR) (23, 34). As these developments are realized, the SeaWiFS record will provide a basis against which future estimates of Earth system elemental cycling can be compared.

26. Unexplained variance in ε is a source of uncertainty in all NPP estimates. For the oceans, ε is generally described as a function of surface temperature (T). To test the sensitivity of our ocean NPP estimates to ε, we recalculated NPP for the SeaWiFS record using the temperature-dependent model of Morel (38). Relative to our ε model (10), the Morel model yielded higher NPP values in the tropics and lower NPP at mid to high latitudes. Mean global NPP was consistently higher by 0.3 ± 0.1 Pg C month⁻¹ for the Morel model, but month-to-month variations in NPP for the two ε models were highly correlated (r² = 0.82). Consequently, the interannual changes in global NPP described herein would be little affected by this change in ε model.
27. NPP estimates reported here are based on globally parameterized remote sensing algorithms for NDVI and NPP that can be extended to the Southern Ocean (39, 40). Developing regionally tuned algorithms may thus improve future estimates of biospheric NPP.
36. NCEP reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, CO, from their Web site at http://www.cdc.noaa.gov/
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